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The Photometric Elements of the Eclipsing Binary EE Pegasi

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New photometric orbital elements are given for the eclipsing binary EE Peg based on 1635 B observations made at the Pine Mountain Astrophysical Observatory of the University of Oregon. The secondary eclispe is total and shallow and results from the eclipse of the smaller, darker star by the larger Am star. Primary eclipse is annular. The pecularities of the spectrum of the Am star are dscussed. The limb-darkening coefficient of the Am component is determined. The rectification procedure is studied with considerable care in part because the A_1 coefficient of the $\cos\theta$ term is positive.

I. INTRODUCTION

PREVIOUS photoelectric photometry on EE Peg has been done by Bakos (1965) and by Catalano and Rodanò (1970). Bakos' analysis suffers from a rather small number of observations, but he obtains a good spectroscopic orbit of the brighter component of this system. His essential spectroscopic elements are $P=2.6282253$ days, $K=86.2\pm0.3$ km/sec, and a very small and probably not significant orbital eccentricity of 0.03.

Catalano and Rodonò observed EE Peg in both B and V, but again the observations are somewhat limited in number consisting of 270 B observations and 254 V observations. Their rectification procedure takes into account only the cosine terms through 2θ and none of the sine terms. They also assumed a limb-darkening coefficient x_g of 0.6 for the larger star. The results of both Bakos and also of Catalono and Rodonò are listed along with those of the present investigation in Table I.

II. THE SPECTRUM OF EE PEG

At the author's request, Dr. Helmut Abt of the Kitt Peak National Observatory obtained two coudè spectra of EE Peg with the 84-inch telescope at a dispersion of 13.4 Å/mm. From these two spectra, Dr. Abt derived an equatorial rotational velocity ($V_e \sin i$) of 30 km/sec "with a possible range of ±3 km/sec." This result is quoted by permission of Dr. Abt in advance of publication. Dr. Abt comments as follows on the spectrum of the brighter component of EE Peg:

> Coudé spectra of EE Peg were compared with similar spectra of standard spectral types, indicating type A2 for the Ca II K line, A5 for the Fe I lines, A9 for Sr II, and earlier than A0 for Sc I. These are the characteristics of an extreme Am star of fairly early spectral type; the star is roughly similar to ζUMa B. These characteristics are consistent with Wellman's comments about the spectrum of EE Peg.

TABLE I. Summary of photometric orbital elements for EE Pegasi.

	Bakos	Catalono and Rodonò	Ebbighausen
r_g	0.166	0.182	0.1695
r_s	0.141	0.107	0.1074
k	0.85	0.59	0.634
i	88°.57	89°.1	88°.61
x_g	0.6 (ass.)	0.6 (ass.)	0.55
L_g	0.784	0.924	0.921
L_s	0.216	0.076	0.079
α_0^{tr}	~1	1.05	1.0520
P	2.6282253 days	2.628208 days	2.6282284 days

III. THE PRESENT PHOTOMETRIC OBSERVATIONS

During the summers of 1968 and 1969, 1635 B observations of EE Peg were obtained on 38 nights with the 15-inch reflector at the Pine Mountain Astrophysical Observatory. The observations are distributed quite evenly over the whole light curve. The large number of observations was obtained in an attempt to derive a definitive set of elements on the Russell model and to make an improved determination of the limb-darkening coefficient for the larger, hotter Am component rather than to assume some value of this coefficient as is usually done. The photomultiplier is an EMI 9524S and the filter combination for the B observations consists of 1 mm of Schott BG12 plus 2 mm of Schott GG13. For all observations, the comparison star was BD $+8°$ 4711 which has nearly the same color as EE Peg. The two stars are separated by about one-quarter degree so it was necessary to correct for differential extinction. A mean value of the extinction coefficient in the B region of 0.35 mag per unit air mass was obtained from the results of many nights and this mean value has been used for all the reductions. The mean epoch of primary minimum and the period obtained from the comparison of the data of both summers are

$$\text{J.D. } 2440286.4329+2.6282284N.$$

It is clear from a plot of all observations that secondary minimum with a depth of about 0.1 mag is a total eclipse of the smaller, darker star of unknown spectral type by the larger, brighter Am star and that primary minimum is an annular eclipse.

All observations were grouped into normal points and are given in Table II in order of decimal parts of the phase. Between phases $0.950P$ and $0.050P$ and between phases $0.450P$ and $0.550P$ (which include re-

TABLE II. Normal point B mag observations of EE Pegasi.

Phase	Δm	$(O-C)$ (0.001 mag)	Phase	Δm	$(O-C)$ (0.001 mag)	Phase	Δm	$(O-C)$ (0.001 mag)	Phase	Δm	$(O-C)$ (0.001 mag)
0.0003	0.630	+4	0.1758	0.023	−2	0.4818	0.102	−2	0.6794	0.024	−1
0.0020	0.628	+4	0.1828	0.019	+1	0.4841	0.106	+1	0.6896	0.023	0
0.0036	0.621	+7	0.1908	0.021	−1	0.4865	0.119	−4	0.7088	0.021	+1
0.0056	0.620	0	0.1963	0.021	−2	0.4892	0.119	+1	0.7234	0.020	+1
0.0079	0.609	0	0.2012	0.020	−1	0.4915	0.123	−1	0.7332	0.017	+4
0.0101	0.581	0	0.2063	0.019	0	0.4936	0.120	+2	0.7417	0.018	+2
0.0126	0.531	−2	0.2104	0.014	+5	0.4957	0.118	+4	0.7514	0.021	−1
0.0146	0.477	0	0.2147	0.016	+3	0.4972	0.124	−2	0.7593	0.019	+1
0.0169	0.419	−1	0.2199	0.016	+3	0.4994	0.122	0	0.7742	0.020	−1
0.0190	0.369	+4	0.2251	0.019	0	0.5030	0.122	0	0.7993	0.021	−1
0.0210	0.324	+3	0.2294	0.022	−3	0.5067	0.123	−1	0.8209	0.021	−1
0.0227	0.290	+2	0.2350	0.018	+1	0.5087	0.125	−3	0.8345	0.026	−6
0.0243	0.256	+3	0.2429	0.016	+3	0.5102	0.123	−2	0.8492	0.023	−2
0.0257	0.234	0	0.2485	0.021	−2	0.5118	0.121	0	0.8560	0.018	+4
0.0279	0.197	+2	0.2534	0.016	+3	0.5136	0.114	+1	0.8621	0.021	+1
0.0302	0.158	0	0.2584	0.020	−1	0.5153	0.111	−1	0.8704	0.021	+2
0.0314	0.145	−2	0.2632	0.022	−3	0.5169	0.107	−2	0.8770	0.024	−1
0.0328	0.126	0	0.2689	0.020	−1	0.5183	0.103	−2	0.8836	0.023	+1
0.0342	0.102	+2	0.2787	0.021	−1	0.5198	0.098	−2	0.8919	0.026	−1
0.0357	0.096	−6	0.2862	0.020	0	0.5216	0.091	−2	0.9003	0.023	+2
0.0372	0.073	−3	0.2919	0.021	−1	0.5237	0.082	+1	0.9069	0.033	−7
0.0386	0.063	−2	0.2967	0.017	+3	0.5257	0.074	0	0.9199	0.030	−2
0.0399	0.052	0	0.3028	0.025	−4	0.5276	0.068	0	0.9419	0.031	−1
0.0420	0.041	−1	0.3131	0.022	−1	0.5300	0.063	−3	0.9494	0.026	+3
0.0443	0.036	−3	0.3222	0.023	−1	0.5322	0.053	0	0.9520	0.032	−2
0.0457	0.030	+2	0.3285	0.025	−3	0.5345	0.048	0	0.9551	0.030	+2
0.0480	0.027	+6	0.3355	0.021	+2	0.5369	0.041	+1	0.9571	0.043	−7
0.0497	0.025	+6	0.3436	0.023	0	0.5393	0.035	+1	0.9589	0.048	−3
0.0520	0.030	+2	0.3520	0.022	+2	0.5412	0.032	+1	0.9607	0.052	+2
0.0555	0.033	−2	0.3590	0.026	−1	0.5433	0.032	0	0.9624	0.065	+2
0.0592	0.036	−5	0.3662	0.024	+1	0.5461	0.030	0	0.9642	0.086	−1
0.0629	0.031	0	0.3790	0.024	+2	0.5480	0.033	−3	0.9663	0.113	0
0.0671	0.033	−3	0.3896	0.024	+3	0.5527	0.031	0	0.9678	0.132	0
0.0709	0.028	+2	0.3996	0.028	0	0.5605	0.031	−1	0.9692	0.150	0
0.0750	0.030	0	0.4095	0.030	−2	0.5683	0.033	−3	0.9709	0.176	−1
0.0799	0.027	+2	0.4191	0.031	−2	0.5748	0.030	−1	0.9729	0.212	−3
0.0858	0.031	−2	0.4275	0.030	0	0.5797	0.029	0	0.9747	0.244	0
0.0903	0.026	+2	0.4324	0.030	0	0.5838	0.031	−2	0.9765	0.280	−2
0.0960	0.027	+1	0.4378	0.030	+1	0.5872	0.028	+1	0.9780	0.308	0
0.1009	0.026	+2	0.4445	0.026	+5	0.5907	0.031	−2	0.9794	0.342	−3
0.1057	0.023	+3	0.4482	0.030	0	0.5953	0.024	+5	0.9811	0.372	+2
0.1109	0.022	+4	0.4514	0.029	+1	0.5987	0.025	+3	0.9826	0.410	+1
0.1157	0.025	+1	0.4538	0.030	−2	0.6019	0.026	+2	0.9841	0.444	+1
0.1195	0.029	−4	0.4559	0.029	+2	0.6051	0.029	−1	0.9856	0.489	−5
0.1239	0.026	−1	0.4584	0.034	0	0.6088	0.029	−2	0.9870	0.518	0
0.1286	0.025	0	0.4609	0.039	−2	0.6134	0.029	−1	0.9882	0.546	0
0.1329	0.026	−2	0.4638	0.044	−2	0.6199	0.027	0	0.9899	0.583	−5
0.1374	0.026	−2	0.4658	0.046	+2	0.6273	0.024	+2	0.9917	0.602	0
0.1419	0.024	−1	0.4682	0.051	+4	0.6369	0.032	−6	0.9932	0.614	−1
0.1476	0.023	0	0.4703	0.058	+3	0.6449	0.027	−2	0.9949	0.627	−5
0.1527	0.022	0	0.4727	0.066	+1	0.6548	0.025	0	0.9971	0.631	0
0.1573	0.023	−1	0.4751	0.080	−3	0.6629	0.026	−2	0.9987	0.635	−2
0.1630	0.024	−3	0.4769	0.086	−1	0.6697	0.025	−1			
0.1686	0.022	−1	0.4799	0.093	+1	0.6756	0.026	−3			

spectively primary and secondary eclipses), the normal points consist of five successive observations in each normal point. Outside these phase ranges (between eclipses), the normals contain ten successive observations each. In the above phase ranges around primary and secondary minima there are respectively 56 and 45 five-point normals. Outside these two phase ranges there are 67 ten-point normals between primary and secondary eclipse and 46 between secondary and primary eclipse. A plot of the normals showed that, within the limits of accuracy of measurement, mid-secondary eclipse occurs at 0.5 phase and that the widths of the two minima are the same. As a result, a circular orbit has been assumed in the analysis of this sytem.

IV. THE RECTIFICATION OF THE LIGHT CURVE

Because of the large amount of data and its low dispersion, it was felt that the rectification procedure should be as rigorous as possible. In order to rectify

TABLE III. Preliminary elements.

$r_g=0.171$	$x_g=0.56$	$i=88\overset{\circ}{.}6$
$r_s=0.108$	$L_g=0.920$ } assumed	
$k=0.63$	$L_s=0.080$ } assumed	

properly the light curve and solve for the final orbital elements, it is first necessary to obtain a preliminary solution. The general procedure used throughout this investigation was that given by Russell and Merrill (1952, RM hereafter).

First of all, the 113 ten-point normal values of $\Delta m(O-C)$ were converted to intensities and the coefficients in the formula

$$\mathcal{I}=A_0+A_1\cos\theta+A_2\cos 2\theta$$

were obtained by a least-squares solution with the results $A_0=+0.9578$, $A_1=+0.0008$, and $A_2=-0.0057$. Note that although A_1 is small and barely significant its value is positive when according to the Russell model, it should be negative. Therefore, it was assumed as a preliminary step that the reflection effect was zero and according to Eq. (154) of RM the intensities of the eclipses were rectified for ellipticity only. Since the C's are tentatively assumed to be zero, Equation (154) in RM has the form

$$\mathcal{I}''=\frac{\mathcal{I}}{0.9578-0.0057(\cos 2\theta)}.$$

From the plot of the rectified normals in the total secondary eclipse, the depth was measured to be 0.080 with the result that $L_s=0.080$ and $L_g=0.920$. Next, the rectified normals in primary eclipse were reflected around phase zero and a smooth curve was drawn through these points. Using the contact times that are rather well defined in secondary minimum holding $L_g=0.920$ and varying the inclination, a few trials with $x_g=0.6$ produced a solution that gave a fairly good fit on the smoothed curve through the reflected normals of primary minimum. With the smoothed curve as a standard, the $(O-C)$'s were calculated for ten phase points along this curve and a least-squares solution using Irwin's (1947) method was performed for the differential corrections to the radii of both components, the inclination and the limb-darkening coefficient x_g. The preliminary elements so obtained are listed in Table III.

V. THE MORE PRECISE RECTIFICATION OF THE LIGHT CURVE

Because outside the eclipses the variable is brighter than the comparison star, the quantity 1.2750 mag was added to the Δm of all normal points which brings the tops of the light curve just below the zero Δm line. Intensities were recomputed for all 113 normals between eclipses and a least-squares solution was performed for A_0 and the coefficients of the Fourier series through 4θ terms for both the cosine and sine terms. The results are shown in Table IV. All coefficients except B_1 and B_4 are considered to be significant. However, it is to be noted that A_1 is positive while according to theory a coefficient of the $\cos\theta$ term arising from reflection must be negative. Therefore, it is concluded that some unidentified "complication" is giving rise to the positive value.

However, one can calculate to a fairly high degree of precision what the C's ought to be. Assuming a spectral type of A3 and calculating the ratio of the depths of the eclipses from the preliminary solution to be $0.420/0.080=5.25$, one obtains from Fig. II on p. 47 of RM and the associated formulas that $G_h=+0.00260$ and $G_c=+0.00966$. From Eq. (105) on p. 48 of RM, one sees that since the inclination is already known to be nearly 90°,

$$C_0=0.3(G_c+G_h)=+0.0037$$

$$C_1=0.4(G_c-G_h)=+0.0028$$

$$C_2=0.1(G_c+G_h)=+0.0012.$$

According to the Russell model, the coefficient of the $\cos\theta$ term in the observations, resulting from reflection, should be -0.0028, but Fourier analysis of the observations yields $A_1=+0.0004$. Therefore, the observational material should be assumed to contain a "complication" appearing as $+0.0032\cos\theta$. *Rectifying* for the theoretical reflection requires a term $+0.0028\cos\theta$, *correcting* for the complication requires a term $-0.0028\cos\theta$, so that the $\cos\theta$ term in equation (153) for $\mathcal{I}'$ is therefore $-0.0004\cos\theta$. In the final rectification to $\mathcal{I}''$, the cosine terms in 3θ and 4θ and the sine terms in 2θ and 3θ are placed in the numerator as further complications and the coefficients are given with the reversed algebraic sign in order to remove these terms. The complete rectification equation is as follows:

$$\mathcal{I}''=\frac{+0.0037-0.0004\cos\theta+0.0012\cos 2\theta+0.0009\cos 3\theta+0.0004\cos 4\theta+0.0006\sin 2\theta+0.0004\sin 3\theta}{0.9804-0.0047\cos 2\theta}. \quad (1)$$

When the rectification is made for the normals between eclipses, the mean of the 67 normals between primary and secondary eclipses is 1.0001 and 0.9998 for the 46 normals between secondary and primary eclipses. No rectification was made for θ in Eq. (73) of RM because for $N=2.6$, $z=0.0111$, and the difference between rectified and unrectified values of θ never exceeds more than $0\overset{\circ}{.}01$.

VI. THE DETERMINATION OF THE FINAL PHOTOMETRIC ORBITAL ELEMENTS

All of the intensity normals in both eclipses were rectified by Eq. (1). A plot of the rectified normals for secondary eclipse shows that there are eight in the total eclipse portion. The mean intensity of these eight normals is 0.9208 ±0.0004 (p.e.). In view of possible uncertainties in rectification and other sources of error it seems safe to adopt $L_g=0.921$ and $L_s=0.079$ with the confidence that these values are significant to the third decimal.

A final least-squares solution was now performed for the 52 five-point normals that are clearly within primary eclipse. In Table II these normals are those with phases 0.0003 to 0.0443 inclusive and 0.9551 to 0.9987 inclusive. Using the preliminary elements given in Table III and the Merrill tables (1950), a calculated intensity was obtained for each normal and also an $(O-C)$. By means of Irwin's (1947) method, differential corrections were obtained by least squares for the preliminary values of the radii, the inclination, and x_g given in Sec. IV. A correction for L_g was not made because it is felt that it was already determined with precision. The application of the differential corrections gives the resulting final elements in the last column of Table I together with those of Bakos and Catalono and Rodonò. No attempt was made to obtain probable errors of the elements obtained in this investigation, but it is estimated that r_g, r_s, and k are significant in the third decimal, i is significant to within 0°1, and x_g is good to within ±0.01 of the value given. θ_e is calculated to be 16°02 and from this the semiduration of both primary and secondary eclipses is 0.0445P on either side, respectively, of phases 0.0P and 0.5P. Because the secondary eclipse is rather shallow no attempt was made to determine x_s and it was assumed to be 0.6. From the value of log G_e obtained in Sec. V and with the aid of Fig. II on p. 47 of RM, the spectral type of the secondary component is probably about F6. From the ratio of the luminosities $L_g/L_s=11.65$, the secondary component is about 2.7 mag fainter than the primary.

Figure 1 is a combined plot of both secondary and primary eclipses. The solid curve for each eclipse is calculated from the elements given in the last column of Table I and includes the rectification restored. The dots are the observed Δm normal points. The vertical lines at the beginning and end of each eclipse curve indicate the calculated limits of each eclipse for a semiduration of 0.0445P. The columns in Table II are respectively the phase in terms of the period, the observed Δm plus 1.2750 mag, and the $(O-C)$ in units of 0.001 mag. From the deviations of the normal points from these two curves it is calculated that for the 51 five-point normals within the limits of primary eclipse the probable error of a single normal is ±0.0018 mag and from the 41 five-point normals within the limits of secondary eclipse the probable error of a single normal is ±0.0013 mag. For the 122 ten-point normals between the two eclipses the probable error of the deviation of a single normal is ±0.0016 mag.

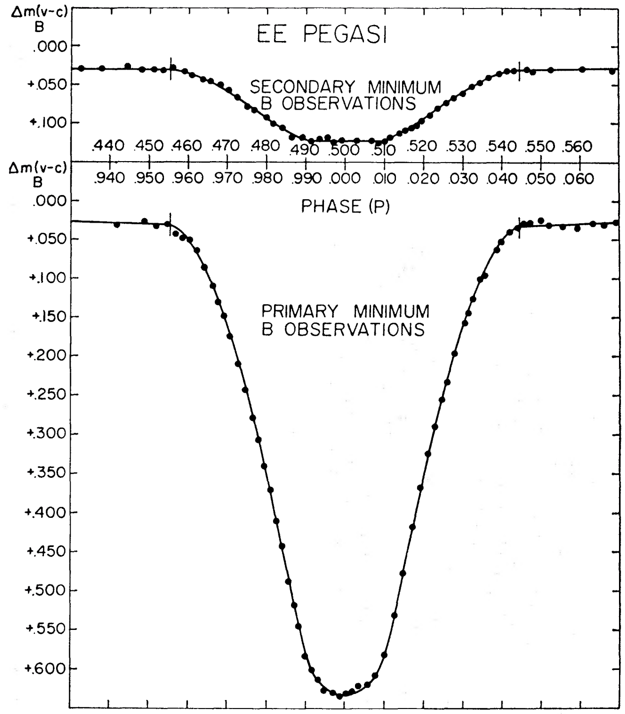

FIG. 1. The computed light curve for EE Pegasi including rectification in the region of both primary and secondary eclipses together with the observed normal point data.

During summers of 1969 and 1970, observations were begun on EE Peg in the U and V regions. The data obtained are not sufficient to determine an accurate light curve, but it is hoped that the remaining observations can be obtained in the 1971 season.

TABLE IV. Fourier coefficients.

$A_0=+0.97665$	
$A_1=+0.00044$	$B_1=+0.00019$
$A_2=-0.00590$	$B_2=-0.00057$
$A_3=-0.00087$	$B_3=-0.00035$
$A_4=-0.00037$	$B_4=-0.00006$

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Photometric Studies of Northern Galactic Clusters. I. Roslund No. 5*

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UBV photometry is presented for 46 stars in the vicinity of the suspected galactic cluster Ros 5. The analysis shows that it is unlikely that Ros 5 is a bona fide open cluster but, rather, it is only a slightly obscured area with a background of relatively early-type stars at a mean distance of approximately 300 pc with a mean reddening of approximately 0.07 mag.

SEVEN new possible galactic clusters found on objective-prism plates taken at the Hamburg Observatory have been listed by Roslund (1960). The detection of the new clusters was made from the areal density of stars, their spectral classes, and their estimated magnitudes. Three of the suspected clusters were studied photographically in two colors by Nelson (1969). Color–magnitudes diagrams showed that both Ros 5 and Ros 6 exhibited relatively well-populated main sequences.

I. OBSERVATIONS

These preliminary results led the writers to carry out a photoelectric investigation of Ros 5 with the 16-inch telescopes at Kitt Peak National Observatory. Roslund has described the cluster as a concentration of relatively early-type stars centered at $\alpha = 20^h04^m.5$ and $\delta = +33°20'$ (1855) with an angular diameter of 40 arc min. The *UBV* observations were obtained for the brighter stars between 20^h00^m and 20^h08^m (1855) of right ascension and between +32°00′ and +34°00′ of declination. Table I lists, in succession, the HD or BD numbers of the program stars, their *UBV* values, the number of observations, their spectral types, and the binary star numbers. The mean error of a single observation, as determined from the internal scatter of the program stars, is $\pm 0^m.01$ in V, $\pm 0^m.01$ in $B-V$, and $\pm 0^m.02$ in $U-B$. Henceforth, mean errors are quoted throughout the paper. The MK spectral types were those determined by Duflot and Fehrenbach (1958) from objective-prism plates; otherwise, the HD spectral types are given.

II. RESULTS

The intrinsic $(B-V)_0$ colors of the B stars were computed using the method described by Crawford (1958). Excluding the three B stars (+33°3760, +33°2768, +33°3773) that are more heavily reddened, a mean color excess of $E(B-V) = 0^m.07 \pm 0^m.03$ was determined. This value of the reddening was applied, with three exceptions, to the later-type stars. The observed $B-V$ colors of the three more heavily reddened B stars were corrected for the effects of reddening by an amount given by their individual color excesses. The first above-mentioned exception (HD 191589) is a more heavily reddened K giant; its intrinsic colors were estimated by projecting the star back to the standard relation for yellow giants. The other two exceptions (+33°3788 and HD 192021) are unreddened F dwarfs. The intrinsic $(U-B)_0$ colors were computed via the expression $E(U-B) = 0.72E(B-V)$ given by Johnson and Morgan (1953).

Figure 1 illustrates the color–color diagram for Ros 5, plotted with the data in Table I. The two solid lines trace the standard relations derived by Johnson and Morgan (1953) for dwarfs and yellow giants, shifted by $+0^m.07$ in $B-V$ and $+0^m.05$ in $U-B$. Although the mean reddening has been removed from the data, the scattering present in Fig. 1 indicates that the reddening is probably variable over the region.

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